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UNPUBLISHED PRELIMINARY DATA

The Zodiacal Light at 5300Å

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ABSTRACT

The surface brightness, the degree, and the orientation of the plane of polarization of the zodiacal light at 5300Å are derived from observations with a photoelectric polarimeter atop 10,012 ft. Mt. Haleakala, Hawaii, between November 1961 and May 1962. Simultaneous observations (with a birefringent airglow photometer) of the 5577Å monochromatic airglow radiation are combined in a 2-parameter analysis to separate the components of the night-sky radiation.

From a comparison of our observations in the plane of the ecliptic with calculations of the brightness and polarization of radiation scattered by single- and multiple-component models of the interplanetary matter (spherical metallic and dielectric particles and electrons: Giese and Siedentopf, 1962; Giese, 1963), we conclude that: (1) dielectric particles can account for the major fraction of both the brightness and polarization of the zodiacal light which we observe; (2) either 5μ (radius) is an approximate upper limit to the particle size distribution, or the size distribution has a steep slope such that there are few large particles; (3) metallic particles are not present in large numbers; (4) if a steady-state distribution of free electrons exists in the interplanetary space at 1 A.U., it cannot have a density greater than some tens of electrons cm^{-3}.

Our observations at high ecliptic latitudes clearly indicate that the zodiacal light covers the entire sky. We find, for example, that the degree of polarization of zodiacal light at the ecliptic pole is approximately .10 as compared with .186 at 90° from the sun in the plane of the ecliptic.

The so-called false zodiacal light is found to be associated with both the morning and evening cones of the zodiacal light, and it is unquestionably associated with the earth's atmosphere. We find no evidence for an enhancement of the principal visible airglow radiations in the zodiacal light, in the false zodiacal light, or in the Gegenschein.

The brightness and polarization of the zodiacal light at high ecliptic latitudes undergo changes which seem to depend upon the inclination of the ecliptic with respect to the horizon and which vary from night-to-night and throughout a given night for observations near the horizon. We suggest that these phenomena (and the false zodiacal light) may be a result of the redistribution of both the total and polarized components of the night-sky radiation by tropospheric scattering.

INTRODUCTION

Photometric observations of the zodiacal light have, over the years, given such widely divergent results that both the fundamental characteristics of the zodiacal light and the inferred nature of the interplanetary medium are highly uncertain. The observational uncertainties arise primarily from: (1) the lack of an acceptable method for separating the individual components of the night-sky radiation field, (2) the lack of a satisfactory formulation for the effects of tropospheric scattering, (3) difficulties associated with the absolute calibration of low light-level extended sources, and (4) limited observational coverage in time and over the sky.

A concurrent photoelectric study of the brightness and polarization of the zodiacal light at 5300Å and the principal monochromatic airglow radiations in the visible was initiated in 1959 as a cooperative program between the High Altitude Observatory and the National Bureau of Standards. With the collaboration of the Hawaii Institute of Geophysics the experiment was transferred in October, 1961 to Mt. Haleakala on the island of Maui, Hawaii (geographic latitude 20°43'N; longitude 156°16'W; elevation 10,012 ft.) to take advantage of the high transparency of the atmosphere at that station. One of the principal reasons for the establishment of the Haleakala facility was the need for a permanent low-latitude observatory where the various components of the night-sky radiation could be observed over long periods of time on a routine basis.

Some of the characteristics of this site, which is part of the scientific complex of the University of Hawaii's Institute of Geophysics, Haleakala Observatory, are:

1. The atmosphere at Haleakala is blanketed from low-lying contaminants by a trade-winds temperature inversion, which is generally 2,000 to 4,000 ft. below the site;

2. The elevation of the site and an unobstructed sea horizon give a depressed horizon of 1.7 degrees, thereby permitting observation of the zodiacal light as close as 20 degrees from the sun without twilight interference;

3. The large number of clear nights (notably during the spring and summer) makes it possible to study diurnal variations in the night-sky radiation field;

4. A paved road makes the site accessible throughout the year; and

5. Commercial power is available at the site.

The results in this paper are based on 30 nights' observations obtained atop Mt. Haleakala from November, 1961 through May, 1962 (Weinberg, 1963b).

INSTRUMENTATION

The zodiacal light photometer utilizes a coupled rotating polaroid-synchronous detector to measure the surface brightness, the degree of polarization, and the orientation of the plane of polarization.

The effective wavelength, 5300Å, of the photometer is determined primarily by a moderately narrow-band (equivalent width = 71Å), high-transmission (78.4%) interference filter. This spectral region was chosen for its lack of intense airglow emission features permitting a more accurate separation of the astronomical and atmospheric components of the night-sky radiation. The field of view, which is determined by a removable field stop located in the focal plane of an achromatic objective, has a diameter of 3.2 degrees (8.04 square degrees on the sky). A field lens focuses an image of the objective on the cathode of a selected (for high AC signal-to-noise ratio) Du Mont 6291 photomultiplier. Focus of the objective rather than the sky on the photocathode reduces the dependence of the response of the system to the location of a discrete source in the field of view.

Clearly, the DC signal generated by the photomultiplier represents the total brightness while the amplitude of the signal modulated by the rotating polaroid is proportional to the brightness of the polarized component. The synchronous (phase-sensitive) detector permits determination of the orientation of the plane of polarization with respect to a predetermined reference direction in the instrument.

The synchronous detector has three pairs of detectors, each of which is alternately on and off for 90 degrees rotation of the polaroid. Each detector pair is 120 degrees (electrically) out of phase with the other pairs, which corresponds to 60-degree geometrical phase shifts, because the rate of rotation of the polaroid is one-half the frequency of modulation of the signal from the photo-detector. The difference in output of the two detectors of each pair is presented on one channel of a 4-channel Sanborn recorder. The remaining detector pairs are similarly recorded. The fourth channel records the total surface brightness (DC signal). Although only two channels in conjunction with the total brightness are required to obtain the polarization information, we make use of the redundancy to reduce any uncertainty resulting from noisy signals (e.g., in regions of low polarization).

A "rejection" circuit (Lee, 1957) was used to reduce the noise level resulting from ion flashback in the photo-detector, from sweeping the photometer across the direction of a bright star, etc. The amount of rejection can be set to chop any signal which is brighter than a given level or has a sharp onset as does a star crossing.

Mounted in tandem with the zodiacal light photometer on an alt-azimuth mounting was a photometer which recorded the brightnesses of the principal airglow radiations in the visible (λ5577, λ5893, λ6300). The principal component of the airglow photometer is a modified Lyot filter which has the property that a line source appears at the output of the photo-detector as an alternating current signal, whereas any continuum emission yields a direct current signal which is easily differentiated. This instrument and the technique used to correct the airglow observations for scattered light and extinction are described in detail by Roach, et al. (1958).

The alt-azimuth mounting was programmed to survey the sky in series of vertical circles or almucantars or by (manually) step-scanning. The almucantar program, which consists of 360-degree scans in azimuth at zenith distances, Z, of 80, 75, 70, 60, 40, and 0 degrees (denoted as a survey), and the manual program were used for all the observations reported on in this paper. A timer scheduled an almucantar survey of the sky every five minutes.

THE OBSERVATIONS AND THEIR ABSOLUTE CALIBRATION

For each of the 30 nights used in this study the atmospheric transparency was classified as good to excellent ($\tau_{eff, 5300Å} \lesssim .15$ (p. 8)). No observations were taken under cloudy or hazy conditions.

Figure 1 shows a portion of an almucantar survey of the night-sky as seen from Haleakala. Position marks are placed on the records at 22.5-degree intervals of azimuth and for each elevation change to facilitate scaling of the records. Such an almucantar program yields information for all ecliptic latitudes and for elongations (at 1-degree intervals) of 25 to 180 degrees from the sun (morning and evening). All the records used in this investigation were scaled by hand, and the readings were tabulated and placed on punched cards for use in interpretive programs on IBM 1401, 709, and 7090 computing equipment.

The DC readings (total brightness) were placed in absolute units by reference to a low light-level, incandescent source which was standardized by comparison with independently-calibrated brightness standards of the National Bureau of Standards, by field measurements of drift-crossings of bright stars, and, independently, by the Institute for Optical Research in Tokyo. From these techniques we estimate that the error in our calibration in units of 10th magnitude (visual) G0 stars per square degree is unlikely to be greater than ($\pm$) 3-5%. The degree and the orientation of the plane of polarization were calibrated by using the incandescent source in conjunction with a pile of (5) glass plates (Weinberg, 1964a).

THE POLARIZED COMPONENT OF THE NIGHT-SKY BRIGHTNESS

The degree of polarization of the zodiacal light, p_{ZL}, corresponds to that fraction of the total zodiacal light brightness (radiance) which is polarized and can be written as

$$p_{ZL} = \frac{I_{\parallel,ZL} - I_{\perp,ZL}}{I_{\parallel,ZL} + I_{\perp,ZL}} \equiv \frac{B_{pol}(ZL)}{B_{obs}(ZL)} \quad , \tag{1}$$

where $I_{\parallel}$ and $I_{\perp}$ are orthogonal components of brightness having their electric vectors parallel and perpendicular, respectively, to the plane through the source, the earth, and the observed point. The measured parameters are the observed brightness, B_{obs}, the orientation of the plane of polarization, χ_Z, and the brightness of the polarized component, B_{pol}. The analysis has been formulated in such a way that χ_Z is used to evaluate B_{pol}. These parameters are used to define a total degree of polarization, p_{tot}, which represents the uncorrected polarization field as seen by the detector:

$$p_{tot} = \frac{I_{\parallel,ZL} - I_{\perp,ZL} + \sum_i (I_{\parallel} - I_{\perp})_i}{I_{\parallel,ZL} + I_{\perp,ZL} + \sum_i (I_{\parallel} + I_{\perp})_i} \equiv \frac{B_{pol}}{B_{obs}} \quad , \tag{2}$$

where ZL and i refer to the zodiacal light and other brightness components, respectively. To obtain the degree of polarization of the zodiacal light from the total degree of polarization, we must consider the possibility that night-sky phenomena other than zodiacal light may contribute to the observed polarization.

Ginzburg (1943) concluded from a study of resonance radiation that the green line of [OI] should not be polarized, and this was confirmed by Bricard and Kastler (1947) from measurements with a Savart-Lyot polariscope. The low brightnesses of the other emission features over the instrument band-pass allow us to disregard them as polarization sources.

Fesenkov (1961) examined the polarization which would result from tropospheric scattering of initially-unpolarized airglow emission and found it to be negligible. No work has been done on the polarization effects from tropospheric scattering of the initially-polarized zodiacal light.

With these facts in mind we assumed in our polarization analysis that all the polarization arises from the zodiacal light and that direct or scattered radiation from the airglow (line and continuum), Milky Way, or integrated starlight only serves to dilute the polarized radiation. Accordingly, $\sum_i (I_{\parallel} - I_{\perp})_i = o$, whereby

$$p_{ZL} = p_{tot} \frac{B_{obs}}{B_{obs}(ZL)} \quad . \tag{3}$$

Since the zodiacal light is only some fraction of the total brightness, $p_{ZL} > p_{tot}$. The considerable disagreement which now exists in measurements of the polarization of the zodiacal light arises primarily from uncertainties inherent in the measurement and determination of the factors forming equation (3). This is further complicated by the use of broadband detection systems (Weinberg, 1963a).

CORRECTIONS TO THE TOTAL RADIATION FIELD

The correction of photometric observations of the zodiacal light involves two major processes. Firstly, the observations must be corrected for radiation scattered into the field of view as well as for extinction between the observer and the source. This is often referred to as correcting the observations to outside the atmosphere. Secondly, the zodiacal light must be separated from the other sources of radiation which combine with the zodiacal light to produce the observed brightness.

The absolute surface brightness of the zodiacal light in a narrow region about 5300Å can be written as

$$B_{\substack{\text{zodiacal}\\ \text{light}}} = \left[B_{obs} - B_{scatt}\right] e^{\tau_{eff} m(Z)} - \left[B_{\substack{\text{integrated}\\ \text{starlight}}} + B_{\substack{\text{galactic}\\ \text{light}}} + aB_{\substack{5577\\ \text{airglow line}}} + \sum_i b_i B(\lambda_i)_{\substack{\text{other air-}\\ \text{glow lines,}\\ \text{bands}}} + B_{\substack{5300\\ \text{airglow}\\ \text{continuum}}}\right], \tag{4}$$

where B_{obs} = observed brightness

B_{scatt} = component of brightness arising from light scattered into the field of view by the atmosphere

τ_{eff} = effective diffuse-source extinction coefficient of the atmosphere

$m(Z)$ = total air mass along the light path at zenith distance Z

a, b_i = instrumental constants.

The remaining symbols and terms are self-explanatory.

Scattering and Extinction

Tropospheric scattering corrections are made on the basis of Ashburn's (1954) application of the X- and Y-functions of radiative transfer (Chandrasekhar, 1950) to Rayleigh scattering of the night airglow. Using the notation of Chamberlain (1961a) we find that

$$B_{scatt} = B(\tau|-1)\left[\frac{\dfrac{B_{trans}(\tau|-\mu)}{B(o|-1)}}{\dfrac{B_{trans}(\tau|-1)}{B(o|-1)} + e^{-\tau}}\right] , \qquad (5)$$

where μ=cos Z, $B(\tau|-1)$ is the observed zenith brightness, $B_{trans}(\tau|-\mu)$ is the diffusely-transmitted brightness scattered through an optical depth τ in a direction specified by μ, and $B(o|-1)$ is the zenith brightness entering the scattering atmosphere. To arrive at equation (5) we have separated the ozone layer from the scattering atmosphere, and we have omitted the ground reflection term, which is negligible at Haleakala. Using the empirically-determined extinction coefficient for the scattering atmosphere at Haleakala, τ = .123, in the $e^{-\tau}$ term and Ashburn's correction terms for the Rayleigh extinction coefficient (for Haleakala), τ_R = .0773, we form the correction factors (Table 1) which, when multiplied by the corresponding component of the observed zenith brightness, will give B_{scatt}. In a subsequent section we describe the method used to separate the atmospheric (h = 100 km) and astronomical (h = ∞) contributions to the observed zenith brightness.

The marked departure of the integrated starlight and zodiacal light from a van Rhijn distribution is the principal uncertainty in this treatment of tropospheric scattering. The corrections for the astronomical component are a factor of 2 smaller than those for the atmospheric component, however, and therefore the accuracy of this technique is of the same order for both components.

Expected contributions to the effective extinction coefficient at Haleakala are listed in Table 2 and are compared with measured values at Haleakala and at Mt. Wilson (compiled by Roach and Meinel, 1955). Ozone absorption was calculated from the absorption coefficient (.069 cm^{-1}) determined by Vigroux (1953) and the average thickness of the ozone layer over Haleakala (.27 atmo-cm) during the period of observation (London, 1962). Absorption by water-vapor was calculated from the absorption coefficient (.0023 cm^{-1}) given by Allen (1955) and the water-vapor content over Hawaii (.2 atmo-cm above 10,000 ft.; Stair and Johnston, 1958). The atmospheric extinction was determined from measurements of a large number of star crossings with the zodiacal light photometer. The average effective extinction coefficient obtained from these measurements is .142, which characterizes the relatively dust-free atmosphere above Haleakala.

The air mass, m(Z), at Haleakala (Table 1) was calculated by combining the ARDC model atmosphere (Minzner, _et al._, 1959) with Bemporad's results for the sea level air mass as given in the Handbook of Geophysics (1960). The extinction factor, $e^{\tau_{eff} m(Z)}$, and the scattering term, B_{scatt}, enabled us to derive the distribution of brightness outside the atmosphere.

Integrated Starlight and Galactic Light

For the integrated starlight we used the results of Roach and Megill (1961), which were determined from star counts in the 206 selected areas (van Rhijn, 1925). A 2-dimensional cubic interpolation was used to find the integrated starlight for the galactic coordinates corresponding to each observation. We found, however, that the highly smoothed star count results, which are based on counts from a very small fraction of the celestial sphere, are not adequate to describe the detailed brightness structure which we observe* at low galactic latitudes ($-20° \lesssim b \lesssim 20°$). This precludes our establishing the distribution of diffuse galactic light at low galactic latitudes by comparing existing star count integrations with the (measured) diffuse brightness associated with the Milky Way. The star count results were used only at high latitudes.

At low galactic latitudes we derived the brightness of the starlight (integrated starlight plus galactic light) by comparing the distributions of total polarization, p_{tot}, north and south of the ecliptic (Weinberg, 1963b). For this portion of the analysis we used only those almucantar scans for which the ecliptic was within 2 degrees of the vertical, thereby minimizing differential scattering corrections. The amount of dilution of p_{tot} at low galactic latitudes is a direct measure of the amount of starlight (as seen at the base of the atmosphere). The distribution of starlight at low galactic latitudes will be discussed in a subsequent analysis.

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*In some regions the star count results indicate a brightness which is greater than the total observed brightness.

Airglow Line Emission at 5577Å

The absolute brightness of the emission feature at 5577Å, which was determined from observations with the aforementioned airglow photometer, was combined with the constant, a, to determine the amount of green line emission seen by the zodiacal light photometer. The constant (see equation (4)) is a function of the filter transmission curve, the quantum efficiency and spectral response of the photodetector, the atmospheric extinction coefficients at 5577Å and 5300Å, and the spectral distribution of the surface brightness of the night-sky. Only when

$$aB_{\substack{5577 \text{ airglow} \\ \text{line}}} \geq .05 \, (B_{obs} - B_{scatt}) \, e^{\tau_{eff} m(Z)} ,$$

do we subtract this component of brightness according to equation (4). In most cases this component is small and can be ignored.

Other Airglow Emission

In the blue region of the spectrum the composite of band wings and small, unresolved bands is relatively strong, and the existence of a strong, continuous airglow spectrum in the green, for which the intensity increases with wavelength, was first indicated by the observations of Barbier, Dufay, and Williams (1954). The observations do not exclude the effects of unresolved bands, but, as Chamberlain (1961b) points out, high dispersion spectra show progressively less structure in the green, which suggests that the continuous emission is stronger in the green than in the blue.

Since we are unable to separate the non-$\lambda5577$ airglow line and band emissions, $\sum_i b_i B(\lambda_i)$, from the airglow continuum, $B_{\substack{5300\\ \text{airglow}\\ \text{continuum}}}$, we combine these terms and define their sum as $B_{\substack{5300\\ \text{airglow}}}$.

After correction for the starlight and $\lambda5577$ airglow terms, we can write equation (4) as

$$B_{\substack{\text{zodiacal}\\ \text{light}}} + B_{\substack{5300\\ \text{airglow}}} = \left[B_{obs} - B_{scatt}\right] e^{\tau_{eff} m(Z)} . \qquad (6)$$

To determine B_{scatt} we must separate the astronomical and atmospheric components of the observed zenith brightness, $B(\tau|-1)$. This, in turn, requires that we know $B_{\substack{5300\\ \text{airglow}}}$.

In the zenith the increased brightness from scattering is very nearly equal to the loss of brightness by extinction, and, when the galactic light and $\lambda5577$ airglow terms can be neglected, we can write

$$B(\tau|-1) = B_{\substack{\text{zodiacal}\\ \text{light}}} + B_{\substack{\text{integrated}\\ \text{starlight}}} + B_{\substack{5300\\ \text{airglow}}} . \qquad (7)$$

After removing the starlight term as previously described, we made use of the sidereal changes of ecliptic and galactic coordinates and a graphical iteration of the zodiacal light and airglow to obtain a self-consistent model in the zenith. This method agrees with results obtained using the techniques of Roach and Meinel (1955).

To separate the zodiacal light and airglow terms in equation (6) we examined differences in the quantity $B_{\substack{\text{zodiacal}\\ \text{light}}} + B_{\substack{5300\\ \text{airglow}}}$ for given values of ecliptic latitude, β, and elongation, ϵ, throughout the night (for different azimuth and zenith distance). If we assume that there are no short-term fluctuations in the zodiacal light we can obtain a relative distribution of $B_{5300 \atop \text{airglow}}$, which, when combined with the zenith airglow component, gives the airglow component at any zenith distance (for each azimuth). To derive the brightness and polarization of zodiacal light we have analyzed every almucantar scan with this polarization dilution and all-night averaging technique.

THE RESULTS AND THEIR INTERPRETATION

In this paper we average the data on the zodiacal light for the 7-month observing period, and we do not take account of possible short- or long-period fluctuations of the zodiacal light. A study is now under way at Haleakala to distinguish the airglow (line and continuum radiation) fluctuations from possible fluctuations of the zodiacal light.

The Average Zodiacal Light in the Plane of the Ecliptic

In Figure 2 we show our results for the average surface brightness of the zodiacal light at 5300Å, in the range of ecliptic latitudes, $-1° \leq \beta \leq 1°$, as a function of elongation. The brightnesses are given in units of the brightness of the integrated solar disk, $\bar{B}_{\odot}$, and in 10th magnitude (visual) G0 stars per square degree (S_{10} (vis) units). The solid curve is the average distribution over the 7-month observing period, and the points correspond to the observations of 4/5 February 1962*.

*In view of the large amount of data, the individual points are shown only for one typical night.

The spread of results for this night is typical of most of the nights (30 in number) that were used in this study. The gradual enhancement toward large elongations is associated with the Gegenschein.

On the basis of our use of a point-by-point analysis of the radiation field by a two-parameter (brightness and polarization) technique, we estimate that the uncertainty in our brightness distribution (Figure 2) is $\pm$ 4-5% at small elongations ($\epsilon < 90°$) and $\pm$ 10-15% at large elongations ($\epsilon > 90°$).

Roach, et al. (1954) have summarized the physical connection and the empirical relationship which exists between the zodiacal light and the F-component of the solar corona. They illustrated this relationship by comparing the brightness distribution laws for the F-corona (based on the approximation of van de Hulst (1947)), for the zodiacal light (as measured in the region $30° < \epsilon < 60°$), and for the intervening region:

$$\log H = 6.22 - 2.5 \log \epsilon \text{ (F-corona)}, \quad (8)$$

$$\log H = 6.17 - 2.22 \log \epsilon \text{ (zodiacal light)}, \quad (9)$$

$$\text{and } \log H = 6.26 - 2.30 \log \epsilon \text{ (interpolation)}, \quad (10)$$

where H is the brightness in units of 10^{-15} times the surface brightness of the center of the sun. The similarity among equations (8), (9), and (10) has often been cited as strong support for the hypothesis that the F-corona and zodiacal light have a common physical origin. A striking similarity or dissimilarity among these equations has little bearing on a common physical origin, however, and a dissimilarity among these equations would, in fact, be a sensitive indicator of the nature and distribution of the interplanetary matter.

In Figure 3 we illustrate this empirical relationship by plotting Blackwell's (1955) measurements of the F-corona and our average brightness distribution as a function of elongation. The coronal measurements were taken from an open aircraft at 30,000 ft. during the eclipse of 30 June 1954. Blackwell and Ingham's (1961) $\lambda 6200$ brightness observations (also shown in Figure 3) are somewhat lower than our $\lambda 5300$ results, which we would expect from a Rayleigh-like distribution of brightness if the interplanetary matter is composed primarily of very small particles. Their results at $\lambda 4470$ are lower (at all elongations) than those at $\lambda 6200$, however, and we therefore cannot use a comparison of our observations as evidence for such a Rayleigh distribution.

In Figure 4 we show the average degree of polarization of the zodiacal light at 5300Å, in the range of ecliptic latitudes, $-1° \leq \beta \leq 1°$, as a function of elongation. The points correspond to the observations of 27/28 and 28/29 December 1961, and the solid curve corresponds to the average distribution over a 2-month observing period when the total polarization was a maximum. Our polarization data for the remaining five months of this investigation is consistent with this body of data, but it has not yet been completely analyzed. We estimate that the uncertainty in our polarization distribution (Figure 4) is unlikely to be greater than $\pm$ .02 in p. In Table 3 we list our observational model for the surface brightness and degree of polarization of the zodiacal light at 5300Å in 2-degree increments of elongation.

As we would expect, we detect no polarization at $\epsilon = 180°$ and $\beta = 0°$. We have detected some cases of negative polarization at large elongations, but our observing and reduction techniques make it difficult to determine accurately the magnitude of these polarizations.

Preliminary Results at High Ecliptic Latitudes

We have analyzed some of our data at high (northern) ecliptic latitudes, and we find the following: (1) the zodiacal light clearly exhibits an appreciable brightness and polarization even at the pole of the ecliptic, (2) the brightness and polarization in off-axis* regions undergo changes which depend upon the inclination of the ecliptic with respect to the horizon, (3) the degree of polarization in off-axis regions decreases to a shallow minimum followed by a slight enhancement toward high ecliptic latitudes, and (4) the position and magnitude of this enhancement also seem to depend upon the inclination of the ecliptic with respect to the horizon.

We frequently measure polarizations, p_{tot}, as high as .03 to .07 at or near the ecliptic pole. Since the zodiacal light contributes approximately one-half of the total surface brightness at the pole, p_{ZL} is approximately .10, as compared with .186 at $\epsilon = 90°$ in the plane of the ecliptic. This result is consistent with other arguments which indicate that the interplanetary matter is concentrated in or near the ecliptic plane.

The considerable variability of our results for observations near the horizon suggests that the redistribution of both the total and polarized components of the night-sky radiation by tropospheric scattering is considerably more complicated than that predicted by Rayleigh scattering

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*Axis refers to photometric axis, i.e., the locus of points of maximum brightness.

of an azimuth-independent van Rhijn brightness distribution. This variability is illustrated in part by the scatter in Figure 5, where we have plotted the zodiacal light brightness at 5300Å (in the range of ecliptic latitudes, $19° \leq \beta \leq 21°$) as a function of elongation for nine different nights. The spread of results for a given morning or evening is quite small, but there are large changes from night to night and from morning to evening.

In the interplanetary space where the optical depth is small, multiple scattering can be neglected, and the orientation of the plane of polarization (E-vector) should be everywhere normal to the arc connecting the sun and the observed point.* While this is confirmed by our observations along the photometric axis of the zodiacal light, recent measurements at Haleakala (Weinberg, 1964b) indicate that there are systematic differences between the observed and calculated orientations of the plane of polarization in off-axis regions. The nature of these differences is still being analyzed.

The Atmospheric Components of the Zodiacal Light

Two unusual aspects of the zodiacal light which have received little or no attention in recent years are the so-called false zodiacal light and the zodiacal twilight. False zodiacal light is the name given to the enhanced brightness near the horizon in the opposite hemisphere from the main cone of the zodiacal light. Zodiacal twilight is the name used to describe the atmospheric component of the zodiacal light at high ecliptic latitudes.

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*There are exceptions to this rule in the vicinity of a neutral point or points.

We find the false zodiacal light to be superimposed on an enhancement of the extra-terrestrial component of the zodiacal light which we observe as we approach the plane of the ecliptic. The brightness of the false zodiacal light, which we see only at large zenith distances, decreases as the Gegenschein ($\epsilon = 180°$) is approached; i.e., as we move toward the zenith. This phenomenon is distinct from the Gegenschein and is <u>unquestionably associated with the earth's atmosphere</u>. It is only seen when the dominant main cone of the zodiacal light is seen in the opposite hemisphere, and it is conspicuous by its absence when these large elongations ($140° \lesssim \epsilon < 180°$) are observed at small zenith distances (near local midnight). We have examined several nights' observations of the evening zodiacal light for this effect, and, contrary to the findings of Fesenkov (1950) and Schmid (1951), we (and Hoffmeister, 1955) also detect the false zodiacal light in the east. We note, however, that the eastern component of the false zodiacal light is less intense than the western component for the small sample of data we have examined. This is probably explained by the fact that the inclination of the ecliptic to the horizon was different in the morning and evening cases.

If the false zodiacal light does, indeed, have an east-west symmetry, then it is not necessary to invoke the existence of an outer atmospheric asymmetry in the form of a gaseous tail (Fesenkov, 1950; Hope: 1953, 1957, 1961). Other possibilities are: (1) the dust cloud about the earth may contribute a small component of brightness in the plane of the ecliptic (Ingham: 1962, 1963; Weinberg, 1963b), and (2) localized sources of brightness (i.e., the zodiacal light) may contribute to a strongly azimuth-dependent brightness distribution of the scattered light, which could account for the fact that the conoid of the false zodiacal light is similar in nature to the main cone of the zodiacal light. It is interesting to note that, in a photometric study of the airglow at College, Alaska, Barbier and Pettit (1952) found a component of scattered light near the southern horizon which they associated with an aurora in the north.

The zodiacal twilight is purportedly characterized by a strong brightness concentration close to the horizon when the ecliptic is inclined at a large angle with respect to the horizon, by an enhancement of the airglow radiations, and by a spreading out or dilatation of the zodiacal light isophotes to high ecliptic latitudes (Fesenkov, 1949; Divari, 1952). Contrary to the findings of Karimov (1950) and Tikhov (1950), Roach, _et al_. (1954) and Divari and Asaad (1959) find no evidence for an enhancement of the principal airglow radiations (λ5577, 5893, 6300) in the zodiacal light. We note that Divari has reversed his original conclusion that, "In the zodiacal light region there occurs a strengthening of atmospheric luminosity ...there is no doubt that in the formation of the zodiacal light an essential part is played by a luminosity _originating_ in the terrestrial atmosphere" (Divari, 1951). We have examined 30 nights' observations with the aforementioned monochromatic airglow photometer at Haleakala, and we also find no evidence for an enhancement of these airglow radiations in the zodiacal light _or in the false zodiacal light_.

Dust and Free Electrons in the Interplanetary Space

Considerable research has been carried out on photometric studies of the zodiacal light over the past two decades in an attempt to gain some knowledge of the steady-state distributions of both dust and free electrons in the interplanetary space. The degree of success is indicated by the fact that one can obtain electron densities of 10 to 10,000 cm^{-3} at the earth's distance on the basis of available observations and existing methods of interpretation.

A number of models of the interplanetary matter have been constructed on the basis of families of solutions to the integral equations describing the brightness and polarization of the zodiacal light (Whipple and Gossner, 1949; Behr and Siedentopf, 1953; Siedentopf, Behr, and Elsässer, 1953; and others). In most of the models the degree of polarization was used only to estimate the number density of free electrons which contributed to the observed brightness of the zodiacal light. The fact that the observed polarization is considerably less than that expected for a component of free electrons was explained on the grounds that the dust component depolarizes the radiation field of the electron component. The widely-held belief that any polarization of the light scattered by interplanetary dust particles of different size and/or composition must be negligible (Behr and Siedentopf, 1953; Elsässer, 1954 a,b) was shown by van de Hulst (1955) to be erroneous.

Laboratory polarization measurements of the light diffusely reflected by stony and metallic particles (Kloverstrom and Rense, 1952) suggested that dust particles could probably account for at least part of the polarization of the zodiacal light. The meteoritic specimens used by Kloverstrom and Rense were quite large, however, and not representative of the interplanetary dust. Subsequent laboratory studies were made of the reflection and polarization by large (1-10 cm) iron and stony meteorites with unmelted surfaces (Richter, 1962a) and of the scattering phase functions of crystals and irregularly-shaped particle fragments (Richter, 1956), of small iron spheres, and of irregularly-shaped dielectric particles in suspended clouds (Richter, 1962b). These studies indicated that the polarization produced by many of these particles and aggregates of particles is a strong function of the phase angle (the complement of the scattering angle) and that the degree of polarization can be quite large for some size distributions and classes of particles. The experimentally-determined scattering phase functions of Richter are in good agreement with Giese's (1961) calculations of theoretical (Mie) scattering phase functions for mixtures of spherical particles of diameter of the order of 1μ (Richter, 1962c).

As a follow-up to Giese's work, Giese and Siedentopf (1962) calculated the surface brightness and degree of polarization for four different groups of models of the interplanetary matter in the plane of the ecliptic. The size distribution law was chosen to be of the form $n(\alpha) = n(\alpha_o)(\alpha/\alpha_o)^{-k}$, where α is the size parameter (=circumference/wavelength), α_o corresponds to the smallest particles present (for a given wavelength), and k is a constant. The brightness and polarization distributions for all models were compared with the observations of Elsässer (1958) and Blackwell and Ingham (1961a)(Figure 7).

The first group of models consisted of six single-component models of spherical particles and free electrons. The metallic, dielectric, and free electron models of this group are shown in Figure 6. The maximum polarizations for the dielectric component models (Figures 6a, 6b) are associated with the Nebelbogeneffekte (haze bow) in the total brightness, $I_1 + I_2$, and are followed by a sharp decrease to negative polarizations at large elongations. The quantity $I_1 + I_2$ corresponds to our use of $B_{\text{zodiacal light}}$ as the surface brightness of the zodiacal light. The other two single-component models (not shown here) consisted of a hypothetical isotropically-reflecting material giving no polarization and a hypothetical metal giving a low brightness. Although our observational results (Table 3) differ from those used by Giese and Siedentopf, we support their conclusion that none of these single-component models can quantitatively produce the observed brightness and polarization of the zodiacal light.

The second and third groups consisted of mixtures of dielectric particles and electrons and of mixtures of dielectric and metallic particles and electrons, respectively. All (3) of the models in each group had the same spatial density distribution law for electrons and electron densities of about 1000 and 300 cm^{-3} at 1 A.U. for the second and third groups, respectively. The composite distributions of brightness and polarization are very similar for the models in each of these groups, and we therefore show only one representative model for each group (Models I and II of Figure 8 and Table 4). Apart from the strong evidence (Blackwell and Ingham, 1961b; Gringauz, *et al.*, 1961; Bridge, *et al.*, 1962; Beggs, *et al.*, 1964; and others) against the existence of an electron component of density 1000 cm^{-3} at 1 A.U., Model I predicts a degree of polarization which is considerably larger than that which we observe. We do not observe the large degree of polarization predicted by Model II in the region $40° \lesssim \epsilon \lesssim 60°$ (from the inclusion of metallic dust particles), and the magnitude of the brightness distribution is too small for all elongations. We therefore conclude that Models I and II do not satisfactorily represent our observations.

The <u>fourth group</u> (one model) consisted of a mixture of an isotropically-reflecting dielectric component and a hypothetical metal. This model is the result of a variation of parameters to reproduce as closely as possible the observational model of Figure 7. Our results (especially at large elongations) rule out any serious consideration of this model.

The "Venus Flytrap" observations of Hemenway and Soberman (1962), which indicate the presence of small (0.1μ) spherical particles between 88 and 168 km, led Giese (1963) to suggest another group of models which involves the presence of large numbers of small particles and no electrons. Model III (Figure 8 and Table 4) is an example of one of these models. The degree of polarization for this model is very similar to that of Model I (i.e., too large), and the magnitude of the brightness distribution is unquestionably too small, but it demonstrates the important fact that <u>electrons are not required to produce a significant degree of polarization</u>.

Giese (1963) justifiably concluded that none of their single-component models quantitatively approximate their limited (in elongation) observational model. The lower polarization of <u>our</u> observational model, however, makes it unnecessary to postulate the existence of large numbers of electrons or metallic particles, and we find that one of Giese's single-component models agrees reasonably well with our observations. This model, which is compared with our observations in Figure 9, is characterized by a very steep particle size distribution and contains a large number ($n_0 = 1.5 \times 10^{-11}$ particles cm^{-3}) of small, Rayleigh-like dielectric particles. The size parameter, α, for this model extends from 1 to 26, which corresponds to a range of particle diameters of 0.17μ to 4.4μ for 5300Å-radiation. Although some electrons and metallic particles do exist in interplanetary space, this comparison suggests that small dielectric particles can account for the major fraction of both the brightness and polarization of the zodiacal light which we observe.

The dielectric-component models show an increase of brightness in the anti-solar direction which may account for all or part of the Gegenschein (see, also, Walter, 1958). As further evidence for this origin of the Gegenschein, we confirm the findings of Roach and Rees (1956) that there is, photometrically, no sharp line of demarcation between the zodiacal light and the Gegenschein. We do not confirm Karimov's (1952) result that the airglow radiations are enhanced in the Gegenschein. We have not analyzed a sufficiently large sample of our data to confirm or deny the existence of some of the other characteristics (e.g., large, short-term brightness fluctuations and westward displacement of the photometric center) which have been attributed to the Gegenschein.

The lack of a large haze bow in the zodiacal light radiation indicates that large spherical particles do not play a dominant role. A small haze bow is associated with the small-particle model (Figure 9), but its magnitude could easily escape detection. We are unable to differentiate between the alternatives that either (1) 5μ is an approximate upper limit to the distribution of those (dielectric) particle sizes which are the major source of zodiacal light, or (2) the particle size distribution has a steep slope such that there are only small numbers of large particles. A more definitive test for the presence of small particles would be the demonstration that there exists a wavelength dependence of the polarized component.

For the extreme assumption of zero polarization by the dust component, one can obtain approximately 600 electrons cm^{-3} at 1 A.U. (Behr and Siedentopf, 1953; van de Hulst, 1956). To obtain the most probable electron density, one must consider the following: (1) only dielectric-component models produce a Gegenschein effect, (2) only dielectric-component models produce an irregular decrease of polarization such as we observe at large elongations, (3) for those models discussed here only dielectric- or electron-component models (or combinations of these) give a maximum polarization at $\epsilon = 70°$ such as we observe, (4) metallic-component models cannot alone account for the observed brightness and polarization, and (5) to include more than some tens* of electrons cm^{-3} at 1 A.U., it is necessary to postulate the existence of a hypothetical non-polarizing dust component.

The similarity between our observations and the theoretical distributions of Figure 9 requires comment on the existence of small spherical particles

*A closer estimate cannot yet be made since electrons and very small particles are nearly equivalent in their polarization properties.

in sufficient number to produce the zodiacal light. The theoretical results are based on spherical particles, because we do not have enough information on the scattering properties of mixtures of differently-shaped particles. Solar wind and photon erosion will tend to make spherical particles, however, and the scattering properties of a large number of small, randomly-oriented, irregularly-shaped particles will probably not differ appreciably from the properties of a mixture of small spherical particles. Finally, the strongest argument for the use of spherical particles is the availability of usable results.

Nicholson (1910) and Proudman (1913) developed the theory for radiation pressure on spherical particles, and they found that there is a small range of particle diameters below the radiation pressure limit for which the radiation pressure force is greater than the gravitational force, which means that these particles will be removed from the solar system by radiation pressure. Smaller particles are allowed to remain in the solar system unless they are removed by other mechanisms (e.g., the Poynting-Robertson effect, coulomb drag, and solar wind effects). The radiation pressure on small metallic particles is much larger than on dielectric particles (Greenstein, 1937), and the range of dielectric particle sizes that will be removed is not known because of uncertainties in the composition, albedo, and efficiency factor for radiation pressure (van de Hulst, 1957).

Recent studies suggest, however, that particles may be removed from the solar system by mechanisms even more efficient than radiation pressure. Wyatt (1963) has proposed that interplanetary grains may acquire an equilibrium negative charge from an imbalance in electron-proton impacts with the grains. Thereafter momentum transfer between close, non-impacting solar protons of the solar wind and the charged grains will introduce a force which may be 100 times as strong as radiation pressure under "hurricane" conditions (a stream velocity of 10^3 km sec^{-1} and a density of 10^4 cm^{-3}). If this hypothesis is correct, the effect of depleting the solar system of these particles should have a noticeable effect on the zodiacal light radiation field during times of intense solar proton events. We have not, as yet, examined our data for any such solar-oriented effects. Wyatt has also examined the Poynting-Robertson effect on these charged grains, and he concludes that the electrostatic P-R drag is approximately 1000 times greater than the radiative P-R drag for the quiet solar wind. Further effects on charged interplanetary grains from Lorentz forces associated with magnetic fields carried in the solar wind are discussed by Parker (1964).

At the present time long-term zodiacal light observations offer the best possibility for learning of the time-scales and efficiencies for the depletion and for the replenishment of these particles, which we must know if we are to obtain the steady-state distribution of particle sizes. There is no reason to expect any single-component model to uniquely represent the nature and distribution of interplanetary matter, but we can infer something of the refractive indices, the particle size distributions, and the number and mass densities from the nature of the observed brightness and polarization distributions. In summary, we conclude that: (1) small dielectric particles can account for the major fraction of both the brightness and polarization of the zodiacal light which we observe, (2) neither electrons nor metallic particles are present in large numbers, and (3) if a steady-state distribution of free electrons exists in the interplanetary space at 1 A.U., it cannot have a density greater than some tens of electrons cm^{-3}.

The Dust Cloud around the Earth

Since 1958 there have been a large number of rocket, satellite, and space probe observations (acoustical impact) of micrometeoric influx (Dubin, 1960; LaGow and Alexander, 1960; Whipple, 1961; Nazarova, 1961; Dubin and McCracken, 1962; Alexander, et al., 1963). The density distributions of interplanetary dust, which are inferred from photometry of the zodiacal light, have been, in all cases, several orders of magnitude smaller than the density distributions obtained from direct measurements of acoustical impact.

This apparent concentration of interplanetary dust near the earth was suggested by de Jager (1955), Beard (1959), and Singer (1961) and was subsequently demonstrated by Whipple (1961), Hibbs (1961), and others from a comparison of zodiacal light results and direct measurements. De Jager (1955) suggested that the earth has a large capture cross-section for zodiacal dust on the basis of the thousand-fold discrepancy between the observed deposit of extra-terrestrial dust and the deposit computed on the basis of observed meteor frequencies. He assumed that all grains which are within 4×10^6 km of the plane of the ecliptic and at a distance of 1 A.U. or more from the sun will eventually be captured by the earth. Taking several density distributions for the zodiacal light material, de Jager found reasonable agreement between his calculated mass deposit of dust and that which was observed ($\sim 10^9$ gm day^{-1}).

An independent confirmation of these results was made by Newkirk and Eddy (1964) as part of an analysis of balloon-borne coronagraph observations to 82,000 ft. From a determination of meteoric influxes and a subsequent comparison with rocket and satellite results, with zodiacal light analyses, and with estimates of meteoric dust suspended in the atmosphere or deposited on the ground, they concluded that: (1) a geocentric concentration of the interplanetary dust of approximately a factor of 10^3 exists in the earth's vicinity, (2) this concentration is most effective for particles in the size range 0.3μ to 10μ, and (3) a majority of the particles in the dust belt are in geocentric, quasi-closed orbits. Newkirk and Eddy's graphical compilation of the various sources of the number densities of interplanetary dust particles (as a function of particle radius) is reproduced with several modifications in Figure 10. The ordinate is the (logarithm of the) number of particles per cm^3 with a radius r (in cm). The large scatter in the zodiacal light results for large particles ($r \sim 10\mu$) does not affect these conclusions, because the agreement is satisfactory for the small particles which are the dominant source of the zodiacal light. If sub-micron ($r \sim 0.1\mu$), dielectric particles exist in the quantity predicted by Giese's (1963) model (Figures 9 and 10), the geocentric concentration for these particles may be only a factor of 10.

CONCLUDING REMARKS

The considerable disagreement which exists in measurements of both the brightness and polarization of the zodiacal light and the difficulties associated with observations in off-axis regions clearly indicate the need for an extensive study of the redistribution of the total and polarized components by tropospheric scattering and of the nature and distribution of the atmospheric radiations. Even with this knowledge of the radiation field we can only obtain families of solutions for the size and spatial distributions and the number and mass densities of the interplanetary matter. The most probable solution can best be derived from a combined study of the results of direct measurements of charged particles and micrometeorite impacts, of the wavelength dependence of the polarized component (especially at large elongations), of the long-term position of the symmetry axis of the zodiacal light, of the nature of the fluctuations in the zodiacal light radiation field, and of the detailed optical characteristics of the interplanetary particles.

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With the collaboration of the University of Hawaii's Institute of Geophysics through the efforts of Walter Steiger, the experiment was subsequently transferred to the more favorable, low-latitude Hawaii site. H. Mack Mann of the NBS was responsible for the building, operation, and maintenance of the Haleakala facility during the period encompassed by our observations.

Franklin Roach placed his airglow data (Fritz Peak and Haleakala), brightness standards, facilities, and time at our disposal to contribute immeasurably to this program. Gordon Newkirk generously provided consultation to this program from its inception and reviewed the final analysis in detail.

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LIST OF FIGURES

Table 1

Air mass, m(Z), and scattering correction factors, $B_{scatt}/B(\tau|-1)$, for Haleakala (λ5300).

Z	m(Z)	Correction Factors h = 100 km	Correction Factors h = ∞
0°	0.690	0.077	0.041
40	0.897	.103	.050
60	1.38	.164	.076
70	2.00	.237	.108
75	2.64	.307	.134
80	3.86	.430	.194

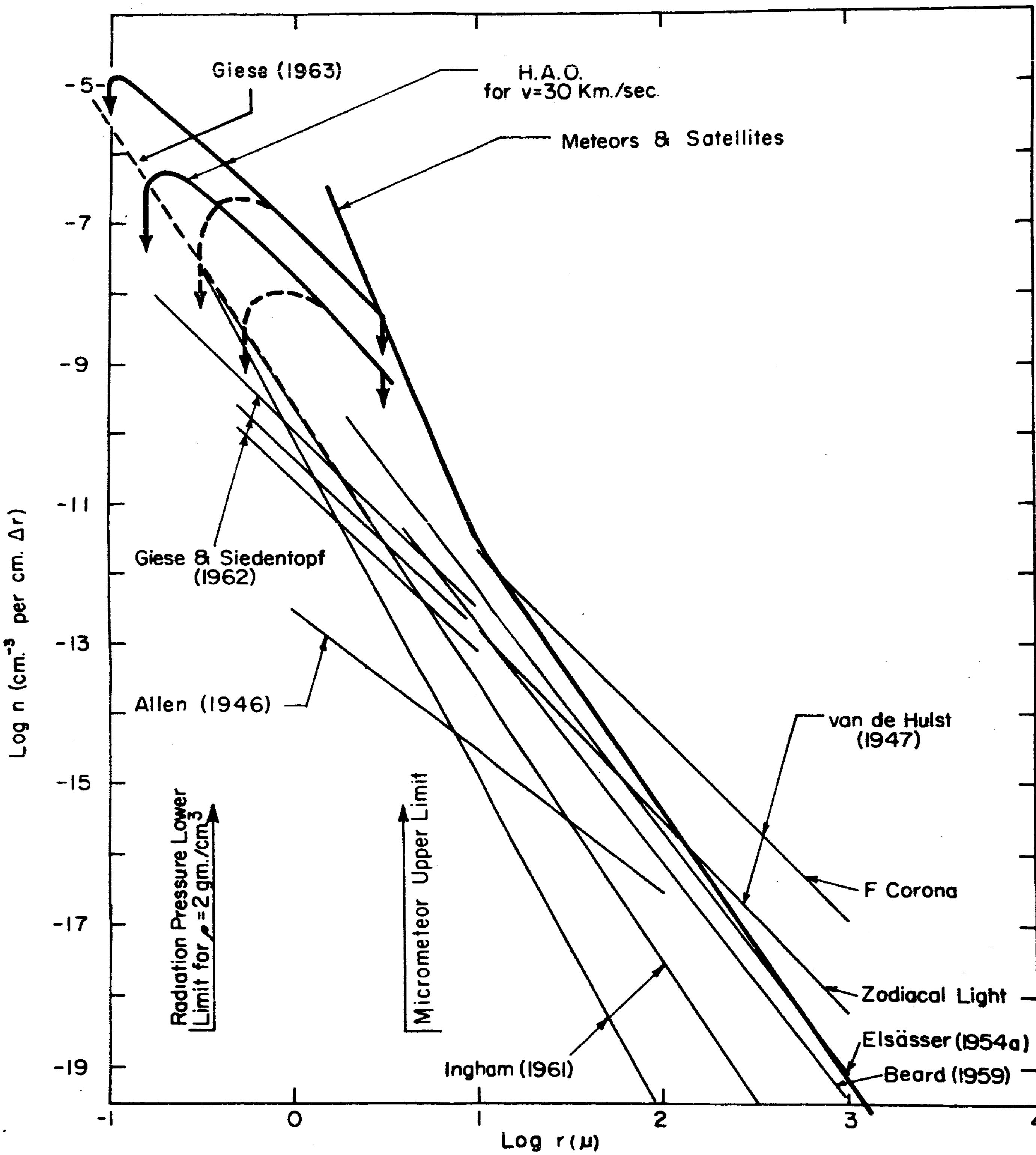

Giese (1963)
H.A.O.
for v=30 Km./sec.
Meteors & Satellites
Giese & Siedentopf
(1962)
Allen (1946)
Radiation Pressure Lower
Limit for ρ=2 gm./cm3
Micrometeor Upper Limit
van de Hulst
(1947)
F Corona
Zodiacal Light
Elsässer (1954a)
Beard (1959)
Ingham (1961)
Log n (cm.^-3 per cm. Δr)
Log r (μ)
-5
-7
-9
-11
-13
-15
-17
-19
-1
0
1
2
3
4

Table 2

Components of the atmospheric extinction coefficient at $\lambda 5300$ (referred to sea level)

Molecular (Rayleigh)	0.112
Ozone (for .27 atmo-cm)	.019
Water-Vapor (for .2 atmo-cm)	.0005
Dust and Haze	?
Sum	.132
Observed (Mt. Haleakala)	.142
Observed (Mt. Wilson)	.164

Table 3

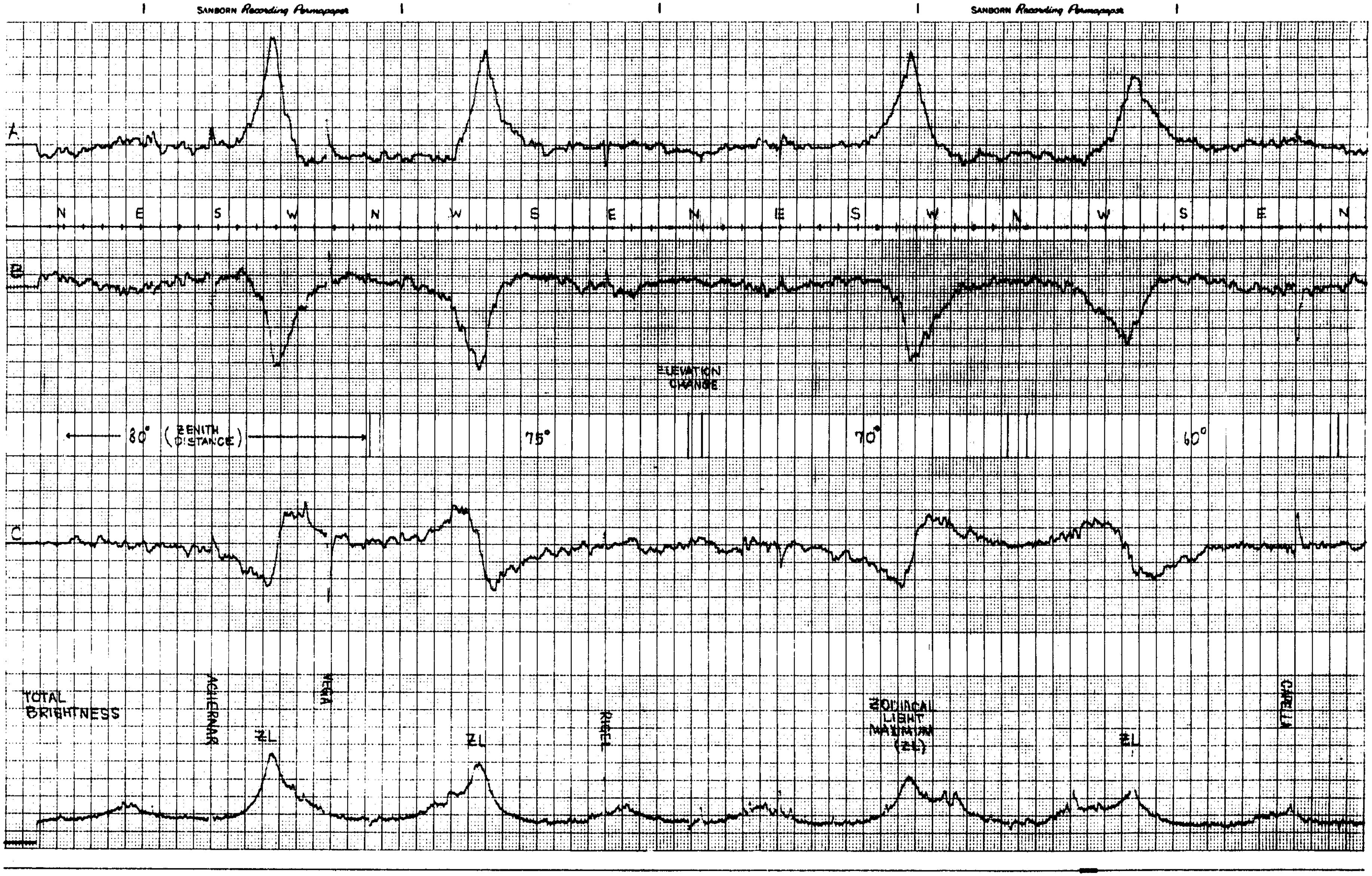
Observational model for the surface brightness and degree of polarization of the average zodiacal light at $\lambda5300$; Haleakala, 1961-62.

ϵ	$B/\bar{B}_{\odot}$ ($\times 10^{-13}$)	S_{10}(vis)	p	ϵ	$B/\bar{B}_{\odot}$ ($\times 10^{-13}$)	S_{10}(vis)	p	ϵ	$B/\bar{B}_{\odot}$ ($\times 10^{-13}$)	S_{10}(vis)	p
30°	10.0	2200	.148	76°	1.50	330	.225	122°	.841	185	.091
32	8.64	1900	.152	78	1.41	310	.222	124	.841	185	.087
34	7.54	1660	.157	80	1.36	300	.217	126	.841	185	.083
36	6.50	1430	.162	82	1.30	285	.213	128	.864	190	.080
38	5.77	1270	.166	84	1.25	275	.207	130	.864	190	.077
40	5.14	1130	.171	86	1.20	265	.200	132	.864	190	.074
42	4.68	1030	.176	88	1.16	255	.193	134	.886	195	.071
44	4.27	940	.181	90	1.14	250	.186	136	.886	195	.068
46	3.89	855	.185	92	1.09	240	.178	138	.909	200	.063
48	3.59	790	.192	94	1.04	230	.171	140	.909	200	.058
50	3.32	730	.197	96	1.02	225	.165	142	.909	200	.052
52	3.09	680	.202	98	1.00	220	.158	144	.909	200	.045
54	2.86	630	.206	100	.977	215	.151	146	.909	200	.038
56	2.68	590	.210	102	.954	210	.144	148	.932	205	.033
58	2.50	550	.215	104	.932	205	.138	150	.932	205	.027
60	2.36	520	.218	106	.909	200	.132	152	.954	210	.023
62	2.20	485	.222	108	.909	200	.126	154	.977	215	.018
64	2.09	460	.224	110	.886	195	.120	156	.977	215	.014
66	1.95	430	.226	112	.886	195	.115	158	1.00	220	.010
68	1.82	400	.228	114	.864	190	.109	160	1.00	220	.006
70	1.75	385	.229	116	.864	190	.105	165	1.04	230	
72	1.64	360	.228	118	.864	190	.100	170	1.09	240	
74	1.57	345	.226	120	.841	185	.095	175	1.11	245	
								180	1.18	260	

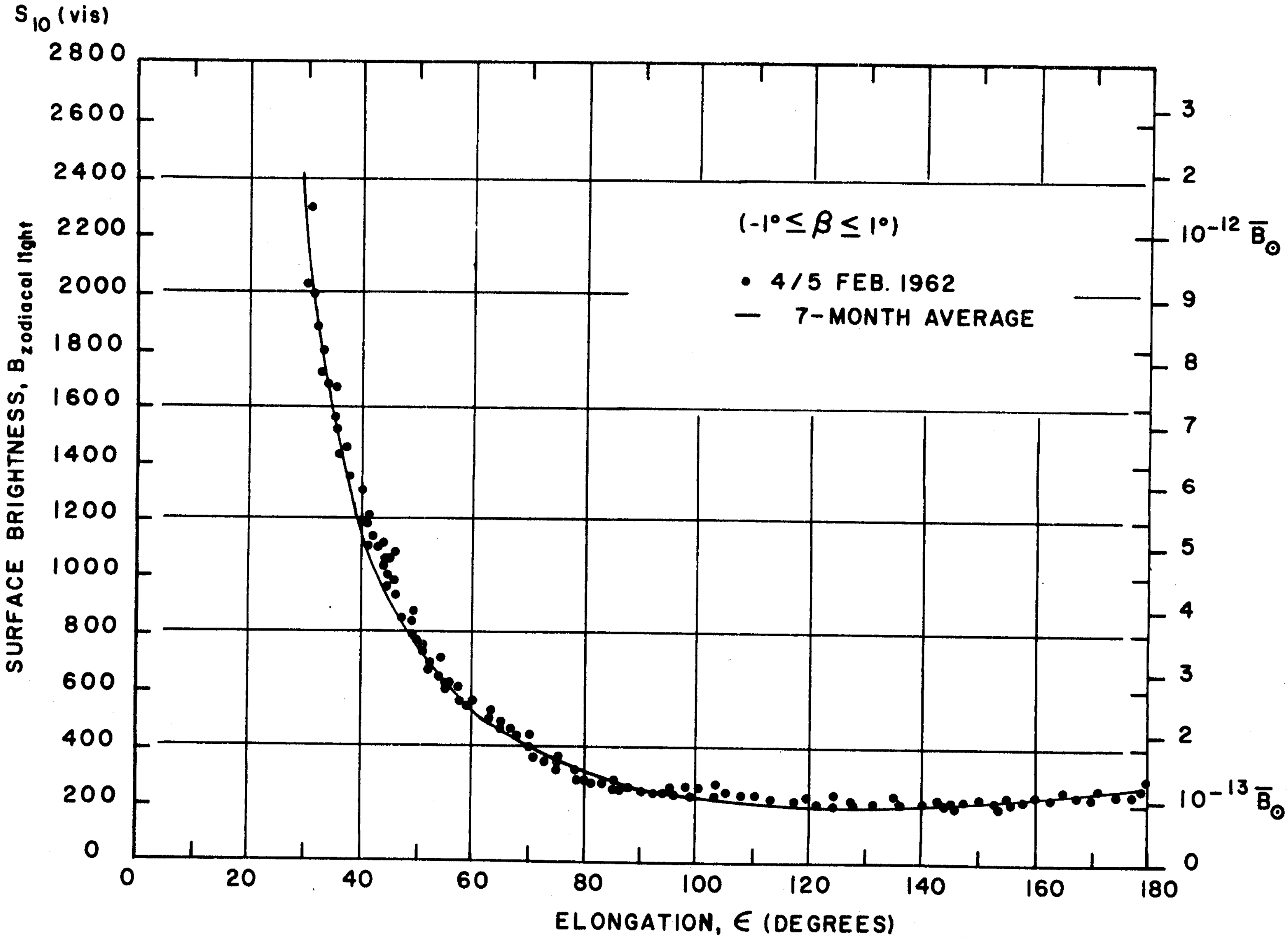
Table 4

The composition of three models of the interplanetary matter, where r is the distance from the sun in A.U., n is the spatial particle density (particles cm^{-3}), and α is the size parameter ($\alpha = \pi d(\mu)/\lambda\ (\mu)$); (from Giese, 1963).

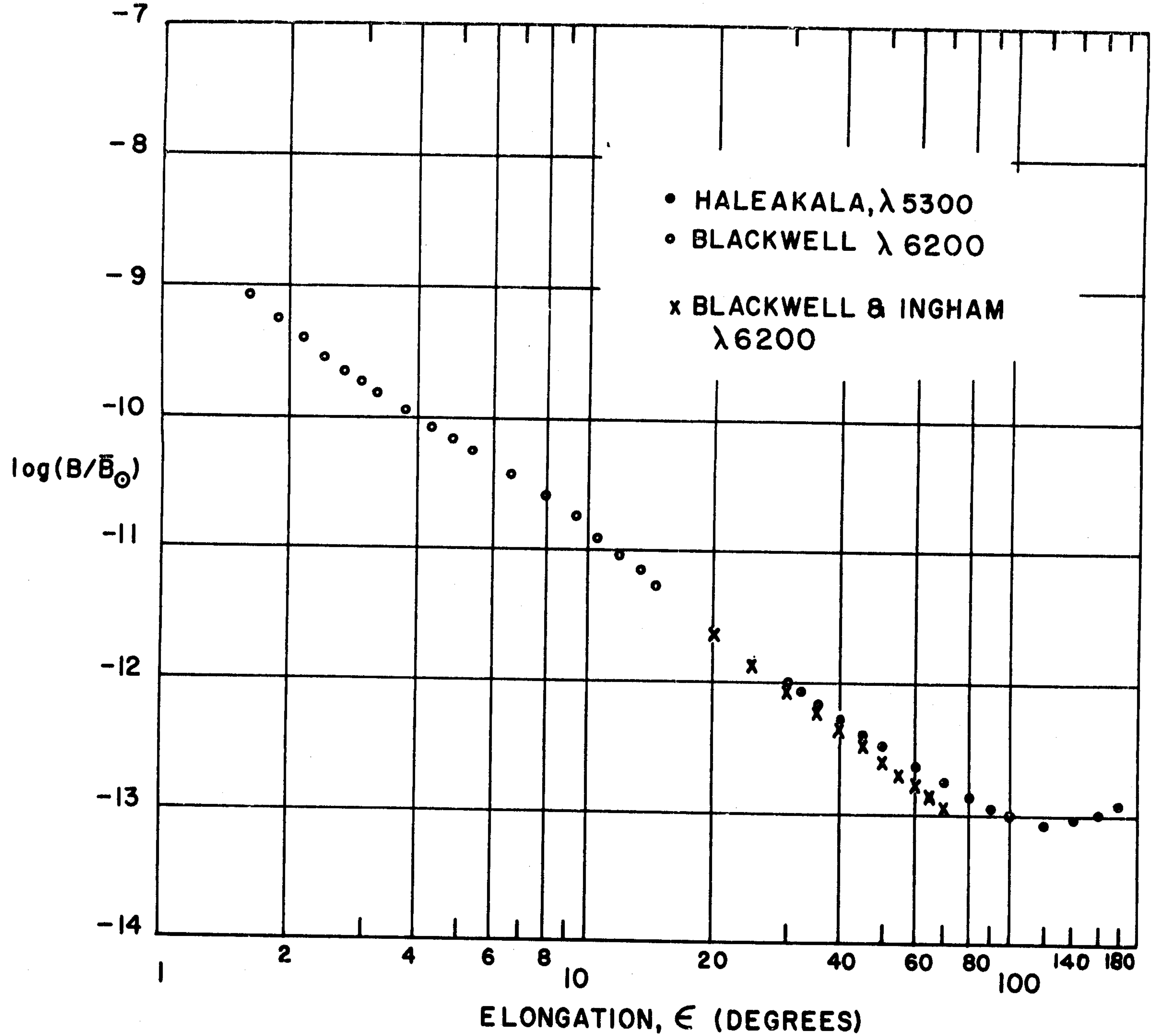
Composition	Material	Refractive Index	Range of Particle Diameters	Distribution Law of Particle Sizes	Spatial Particle Density
Model I	Dielectric	1.33	1.9 - 19μ	$\sim \alpha^{-2.5}\, d\alpha$	$n = \frac{10^{-15}}{r^{3.5}} + 5 \times 10^{-15}$
	Electrons	----	---------	----------	$n = \frac{0.5}{r^3} + \frac{10^3}{r^{0.5}}$
Model II	Dielectric	1.33	1.9 - 19μ	$\sim \alpha^{-2.5}\, d\alpha$	$n = \frac{3 \times 10^{-15}}{r^3}$
	Metal	1.27-1.37i	0.3 - 19μ	$\sim \alpha^{-2.5}\, d\alpha$	$n = \frac{1.5 \times 10^{-13}}{r^{0.5}}$
	Electrons	----	----------	-----------	$n = \frac{5}{r^3} + \frac{300}{r^{0.5}}$
Model III	Dielectric	1.33	1.6 - 6.4μ	$\sim \alpha^{-2}\, d\alpha$	$n = \frac{3 \times 10^{-15}}{r^3}$
	Dielectric	1.33	0.16-4.1μ	$\sim \alpha^{-4}\, d\alpha$	$n = \frac{6 \times 10^{-12}}{r^{0.5}}$
	Metal	1.27-1.37i	0.16-4.1μ	$\sim \alpha^{-4}\, d\alpha$	$n = \frac{1.8 \times 10^{-12}}{r^{0.5}}$



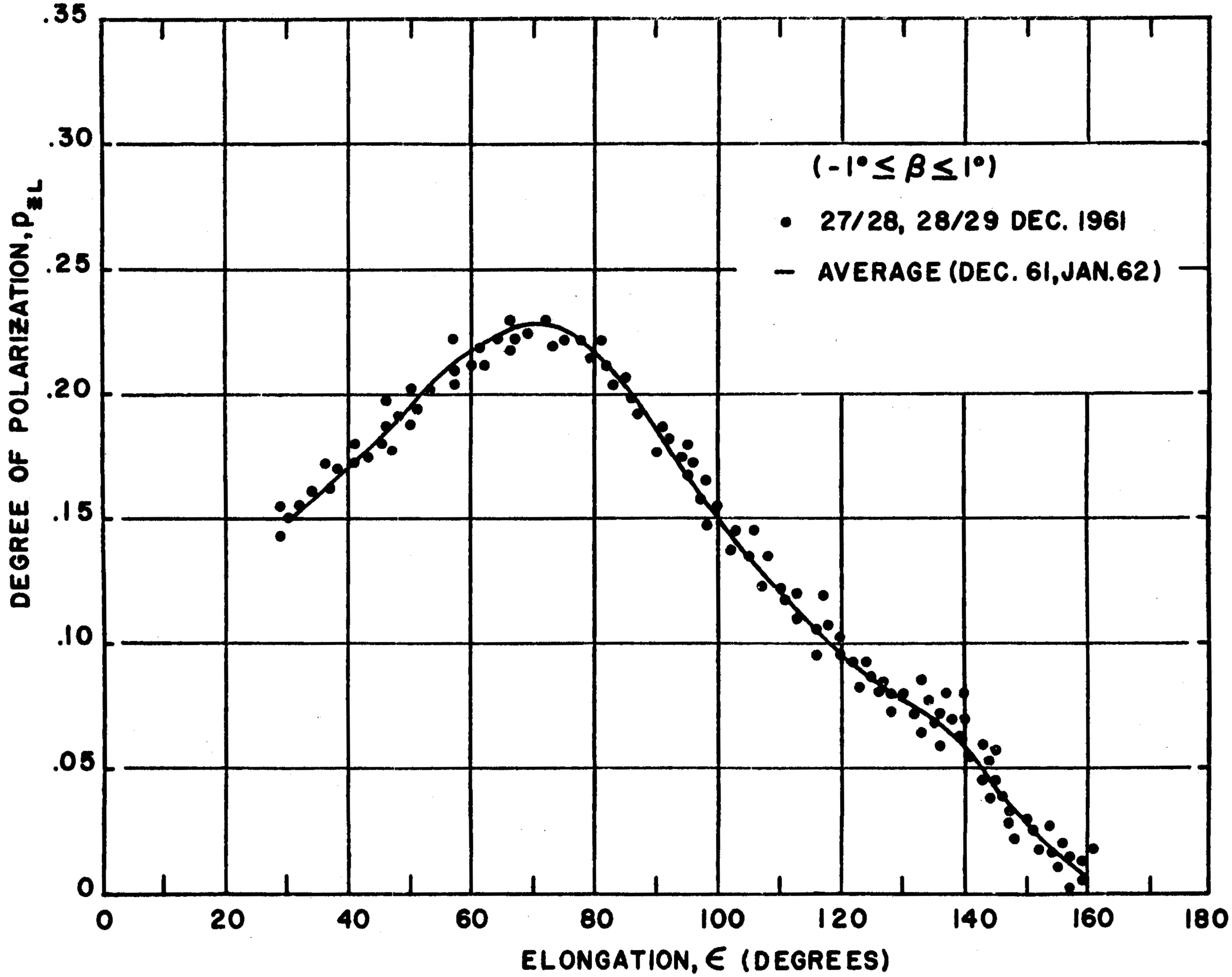
SANBORN Recording Permapaper
A
B
C
N E S W N W S E N E S W N W S E N
ELEVATION CHANGE
80° (ZENITH DISTANCE)
75°
70°
60°
TOTAL BRIGHTNESS
ACHERNAR
VEGA
RIGEL
CAPELLA
ZL
ZODIACAL LIGHT MAXIMUM (ZL)



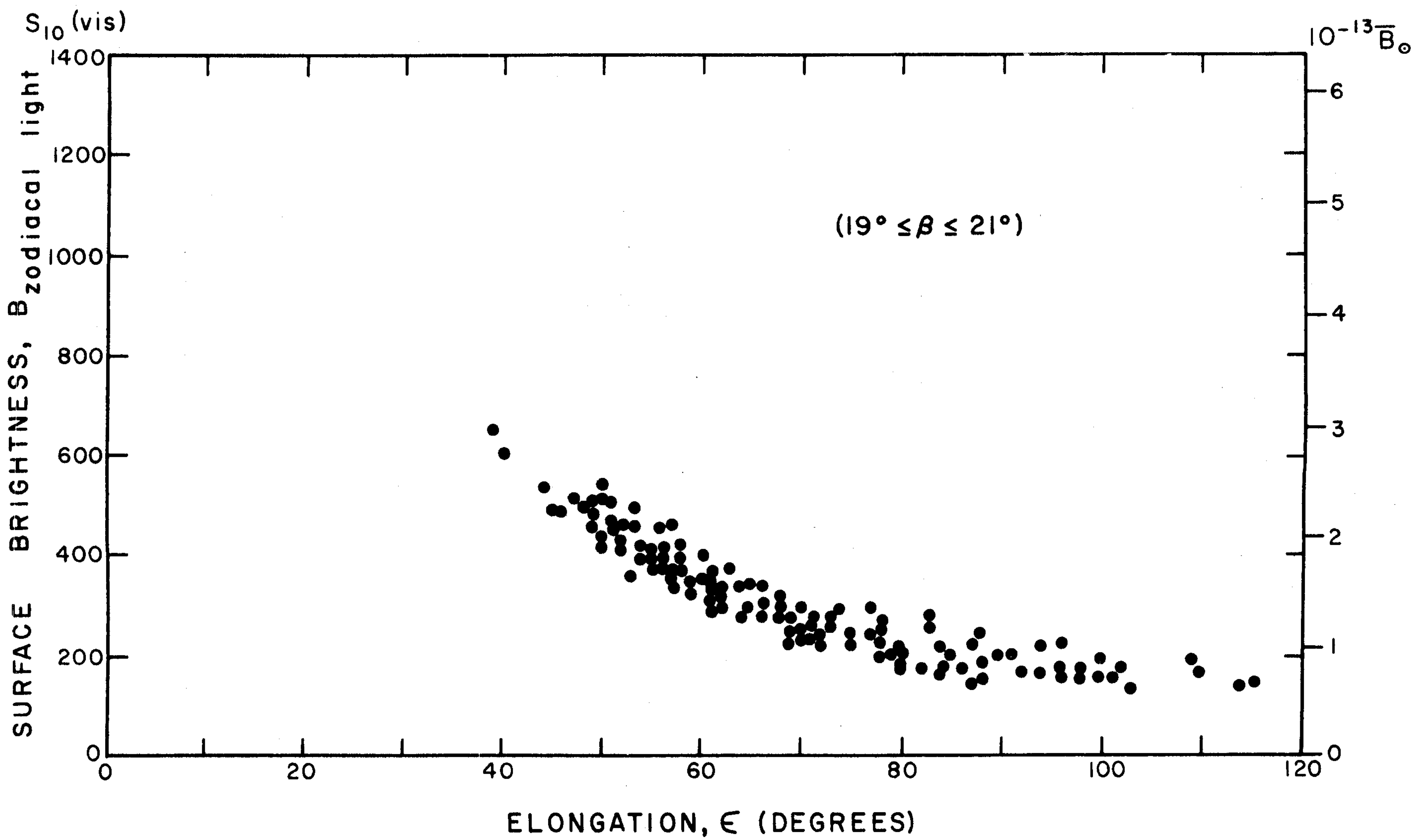
S_{10} (vis)
SURFACE BRIGHTNESS, $B_{zodiacal\ light}$
2800
2600
2400
2200
2000
1800
1600
1400
1200
1000
800
600
400
200
0
$(-1° \leq \beta \leq 1°)$
• 4/5 FEB. 1962
— 7-MONTH AVERAGE
3
2
$10^{-12}\,\overline{B}_\odot$
9
8
7
6
5
4
3
2
$10^{-13}\,\overline{B}_\odot$
0
0
20
40
60
80
100
120
140
160
180
ELONGATION, ϵ (DEGREES)



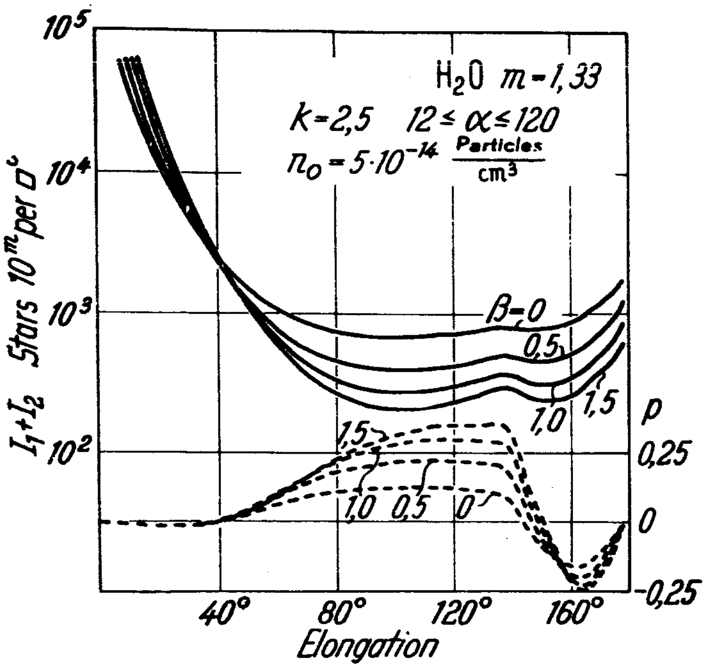
• HALEAKALA, λ 5300
∘ BLACKWELL λ 6200
x BLACKWELL & INGHAM λ 6200
-7
-8
-9
-10
-11
-12
-13
-14
log(B/B̄⊙)
1
2
4
6
8
10
20
40
60
80
100
140
180
ELONGATION, ∈ (DEGREES)

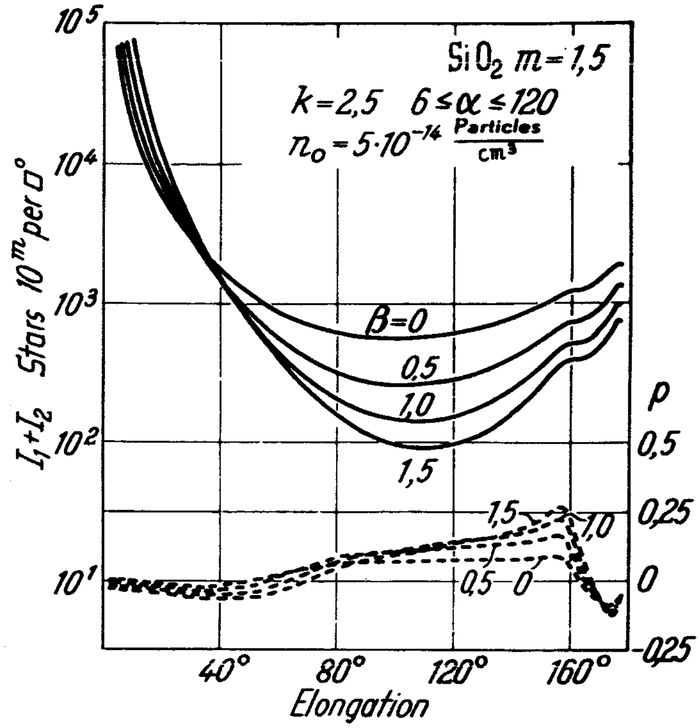


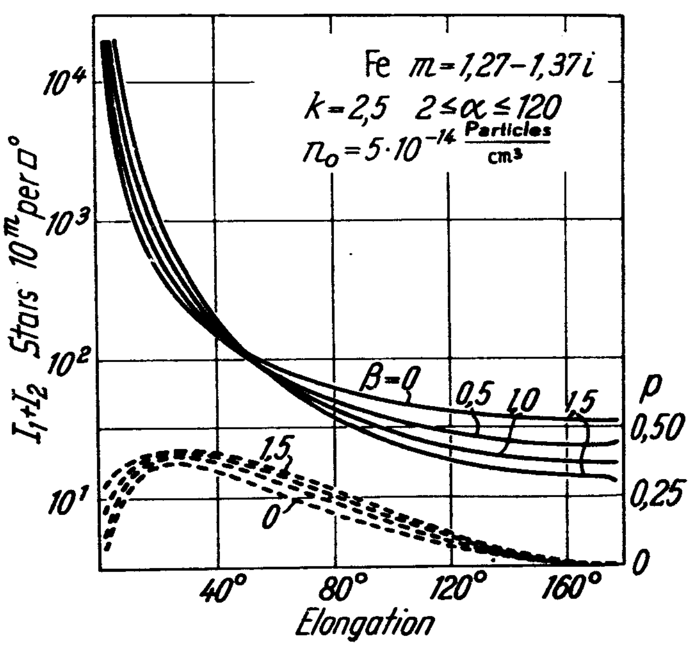
DEGREE OF POLARIZATION, $p_{\equiv L}$
.35
.30
.25
.20
.15
.10
.05
0
0
20
40
60
80
100
120
140
160
180
ELONGATION, ϵ (DEGREES)
($-1° \leq \beta \leq 1°$)
27/28, 28/29 DEC. 1961
AVERAGE (DEC. 61, JAN. 62)

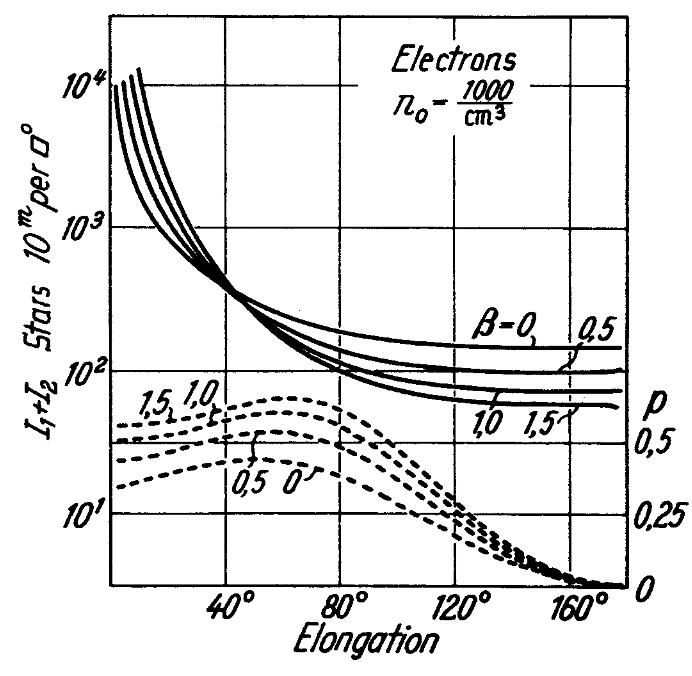


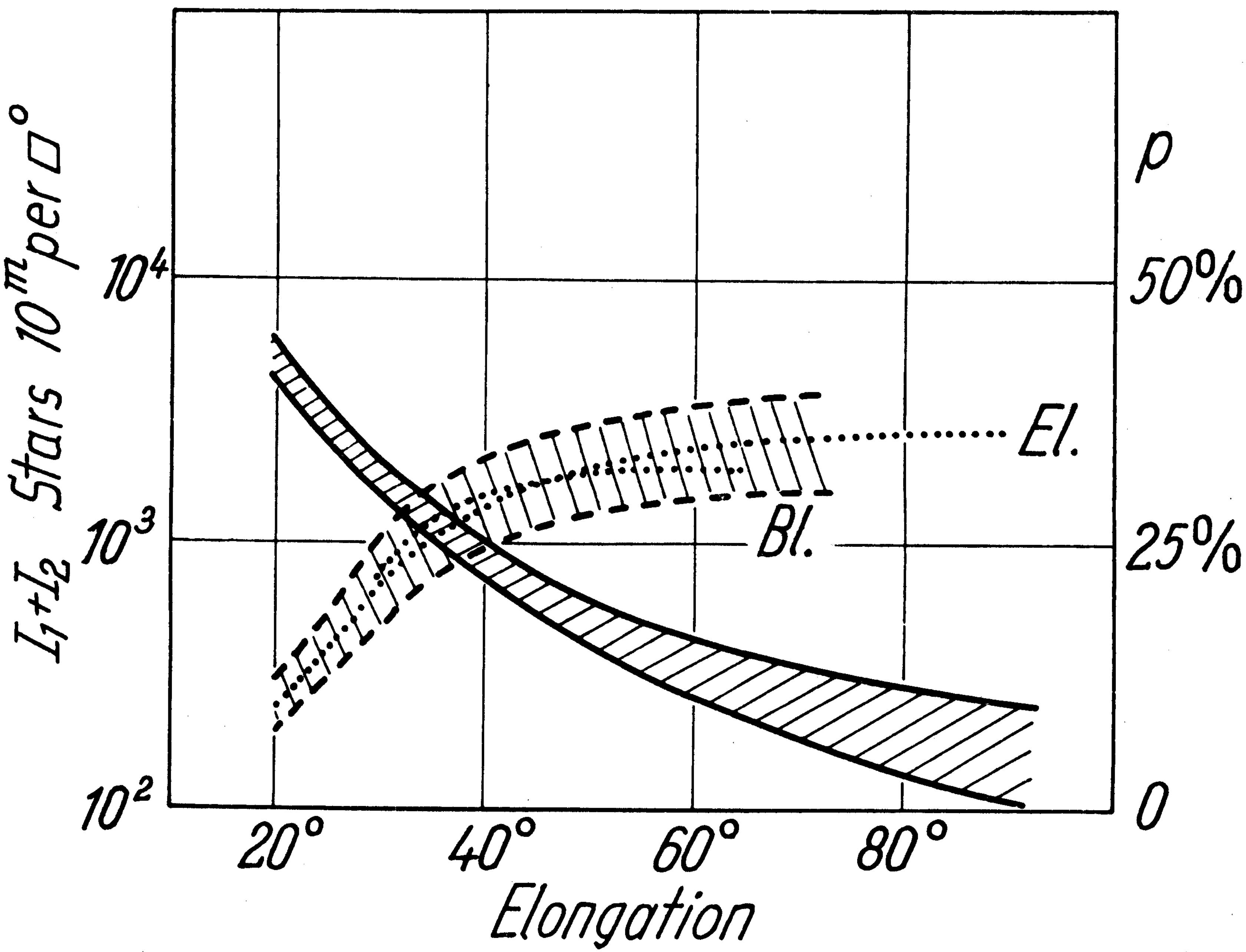
S10 (vis)
10-13 B⊙
SURFACE BRIGHTNESS, B zodiacal light
(19° ≤ β ≤ 21°)
ELONGATION, ϵ (DEGREES)
0
200
400
600
800
1000
1200
1400
20
40
60
80
100
120
1
2
3
4
5
6

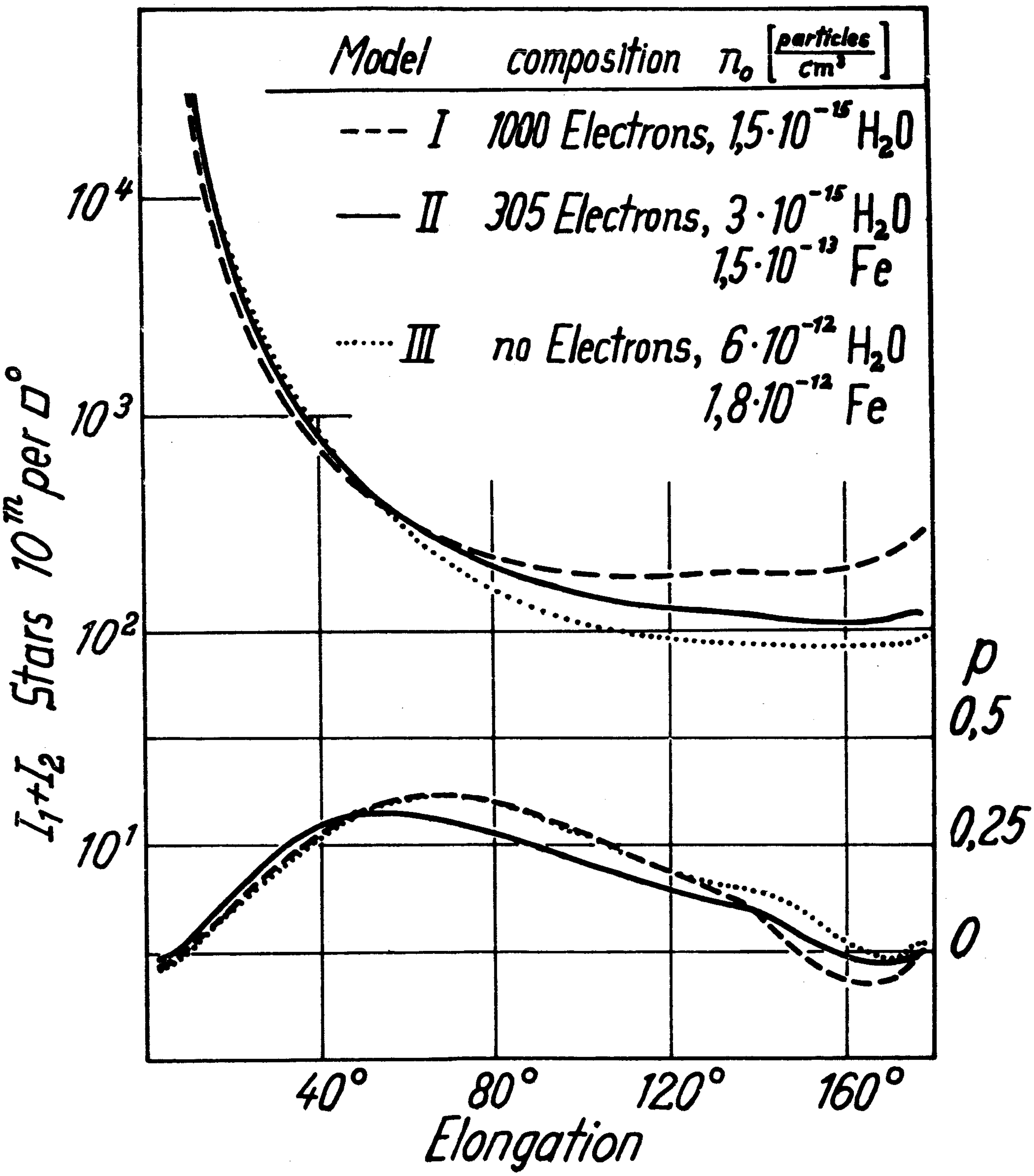

H_2O $m=1,33$
$k=2,5$ $12 \leq \alpha \leq 120$
$n_o = 5 \cdot 10^{-14}$ Particles/cm³
I_1+I_2 Stars 10^m per □°
p
$\beta=0$
0,5
1,0
1,5
Elongation


SiO_2 $m=1,5$
$k=2,5$ $6 \leq \alpha \leq 120$
$n_o = 5 \cdot 10^{-14}$ Particles/cm³
I_1+I_2 Stars 10^m per □°
p
$\beta=0$
0,5
1,0
1,5
Elongation

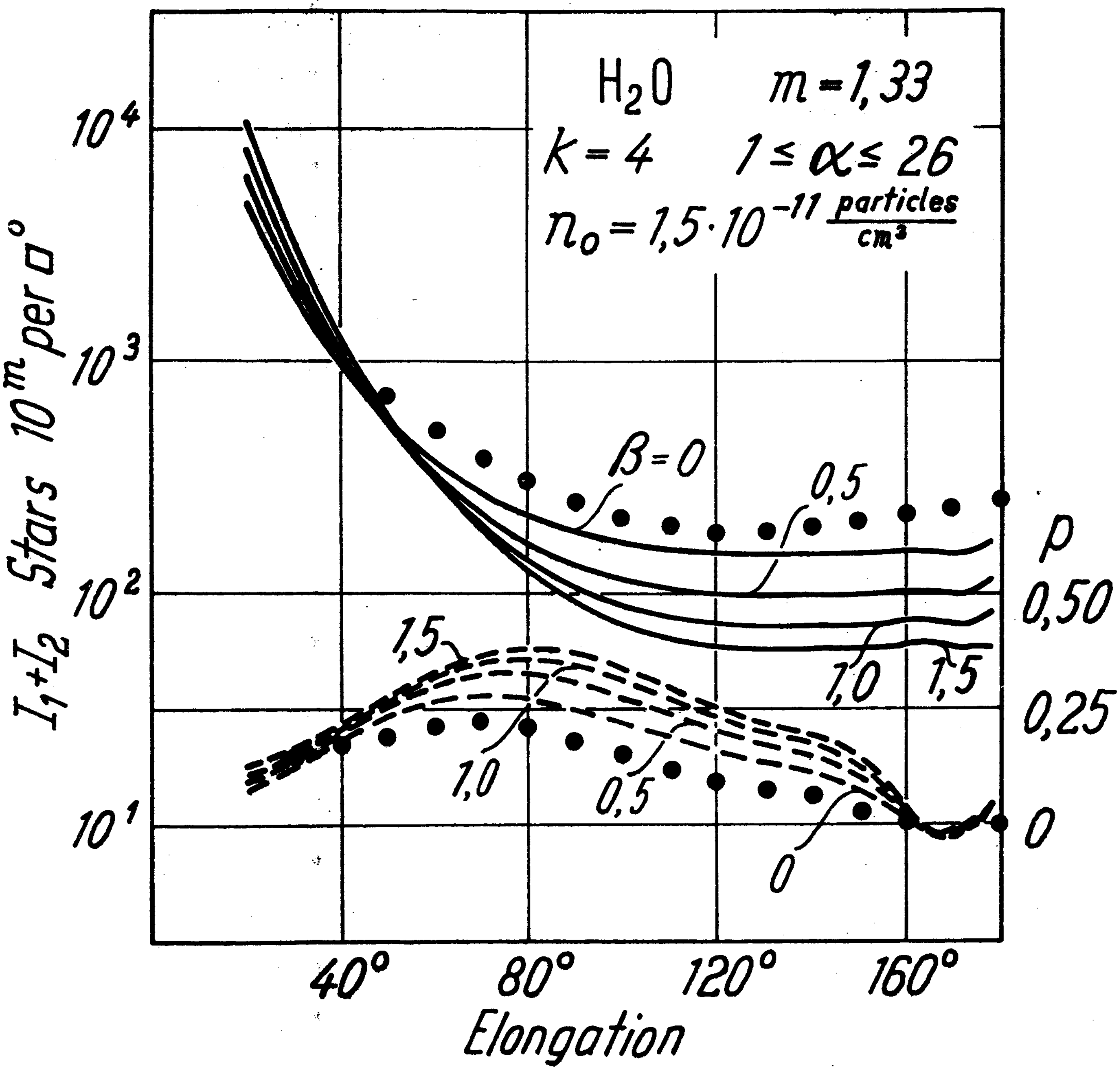

Fe $m=1,27-1,37i$
$k=2,5$ $2 \leq \alpha \leq 120$
$n_o = 5 \cdot 10^{-14}$ Particles/cm³
I_1+I_2 Stars 10^m per □°
p
$\beta=0$
0,5
1,0
1,5
Elongation


Electrons
$n_o = \frac{1000}{cm^3}$
I_1+I_2 Stars 10^m per □°
p
$\beta=0$
0,5
1,0
1,5
Elongation


I_1+I_2 Stars 10^m per □°
10^4
10^3
10^2
p
50%
25%
0
El.
Bl.
20°
40°
60°
80°
Elongation



Model composition n_o [particles/cm³]
--- I 1000 Electrons, $1{,}5\cdot10^{-15}$ H_2O
— II 305 Electrons, $3\cdot10^{-15}$ H_2O
$1{,}5\cdot10^{-13}$ Fe
······ III no Electrons, $6\cdot10^{-12}$ H_2O
$1{,}8\cdot10^{-12}$ Fe
10^4
10^3
10^2
10^1
I_1+I_2 Stars 10^m per □°
p
0,5
0,25
0
40°
80°
120°
160°
Elongation



H_2O $m = 1,33$
$k = 4$ $1 \le \alpha \le 26$
$n_0 = 1,5 \cdot 10^{-11} \frac{\text{particles}}{\text{cm}^3}$
$I_1 + I_2$ Stars 10^m per $\square^\circ$
10^4
10^3
10^2
10^1
$\beta = 0$
0,5
1,0
1,5
0
p
0,50
0,25
40°
80°
120°
160°
Elongation